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Interaction- and charge-changing cross sections for neutron-rich $^{63-80}$Cu isotopes toward the derivation of neutron skin thickness

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ABSTRACT

We have measured the interaction cross sections (σ_I) and charge-changing cross sections (σ_{cc}) for neutron-rich copper isotopes with mass numbers $A = 63 - 80$ using the transmission method at the RIBF facility, RIKEN. From these values, we aim to derive the proton distribution radius (R_p) and the neutron distribution radius (R_n) for each isotope through subsequent analysis. Then, we plan to determine the neutron skin thickness ($\Delta R_{np} = R_n - R_p$) for each isotope. These results will provide a new constraint on the symmetry energy parameter L of the equation of state (EoS) of nuclear matter and contribute to a deeper understanding of the nuclear structure of exotic nuclei.

1. Introduction

In this paper, we present the results of interaction cross sections (σ_I) and charge-changing cross sections (σ_{cc}) measured for neutron-rich $^{63-80}$Cu isotopes. The background and motivation for this study are described below.

The neutron skin thickness (ΔR_{np}), defined as the difference between the neutron distribution radius (R_n) and the proton distribution radius (R_p) of a nucleus, is a fundamental property that provides critical insights into the equation of state (EoS) of nuclear matter [1]. In particular, ΔR_{np} is strongly correlated with the parameter L, which characterizes the density dependence of the nuclear symmetry energy in the EoS [2,3]. Therefore, precise measurements of the neutron skin thickness can constrain the symmetry energy. Furthermore, systematic measurements across a long chain of isotopes are thought to be a promising approach for constraining the symmetry energy [4].

For the systematic measurement of neutron skin thickness, we employ a method that involves simultaneous measurements of the interaction cross sections (σ_I) and charge-changing cross sections (σ_{cc}). The interaction cross sections enable the determination of the nuclear matter radii ($R_m \equiv \sqrt{\frac{1}{A}\left(Z R_p^2 + N R_n^2\right)}$) by using the Glauber model [5]. Similarly, charge-changing cross sections enable the extraction of proton distribution radius (R_p) for each isotope [6]. By deriving both R_m and R_p, we can calculate the neutron skin thickness ($\Delta R_{np} = R_n - R_p$) for each isotope. The advantage of this method lies in its characteristic of achieving high-statistics measurements, enabling the access to very neutron-rich isotopes, where the neutron skin is more developed. Thus, this method provides a unique approach to systematically constrain the symmetry energy parameter L by offering a comprehensive dataset of neutron skin thickness across many isotopic chains. Moreover, the comprehensive examination of both matter and proton distribution radii will contribute to a deeper understanding of nuclear structure in exotic nuclei. In particular, copper isotopes exhibit odd-even staggering in charge radii [7], a phenomenon that is not yet fully understood, making them especially intriguing for further investigation including insights from neutron distribution radii.

2. Experiment and analysis

We performed the experiment at the RIKEN Radioactive Isotope Beam Factory (RIBF) using the BigRIPS fragment separator (Fig. 1). A primary beam of ^{238}U was accelerated to 345 MeV/u impinged on a 5 mm-thick beryllium (Be) target at the F0 focal plane to produce secondary beams. The resulting secondary beams were separated using the BigRIPS separator.

The nuclear species of incoming particles were identified between the F3 and F5 focal planes using the time-of-flight (TOF), magnetic rigidity ($B\rho$), and energy loss (ΔE) methods [8]. Particle position was measured using the PPAC detectors placed at each focal plane [9]. For the energy loss measurement, the multi-sampling ionization chamber (MUSIC) placed at F3 was used [10]. A wedge-shaped carbon (C) target with a thickness of 1.8 g/cm^2 was installed at the F5 focal plane as the reaction target.

The interaction cross sections (σ_I) were determined from the transmission rates with ($T_{I,in}$) and without ($T_{I,out}$) the target using the following relation:

$$\sigma_I = -\frac{1}{t} \ln \left(\frac{T_{I,in}}{T_{I,out}} \right), \tag{1}$$

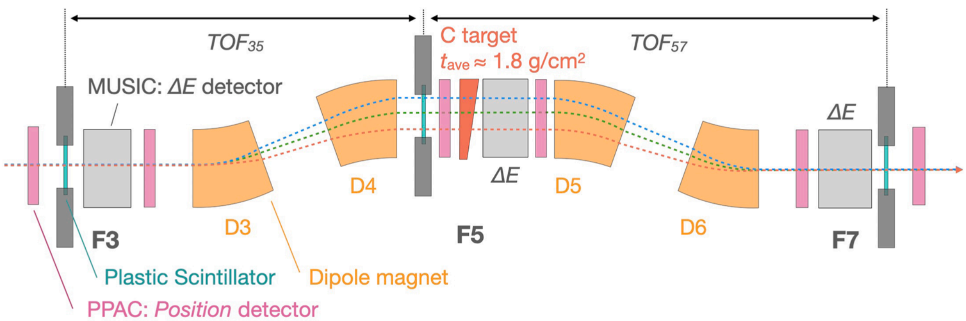
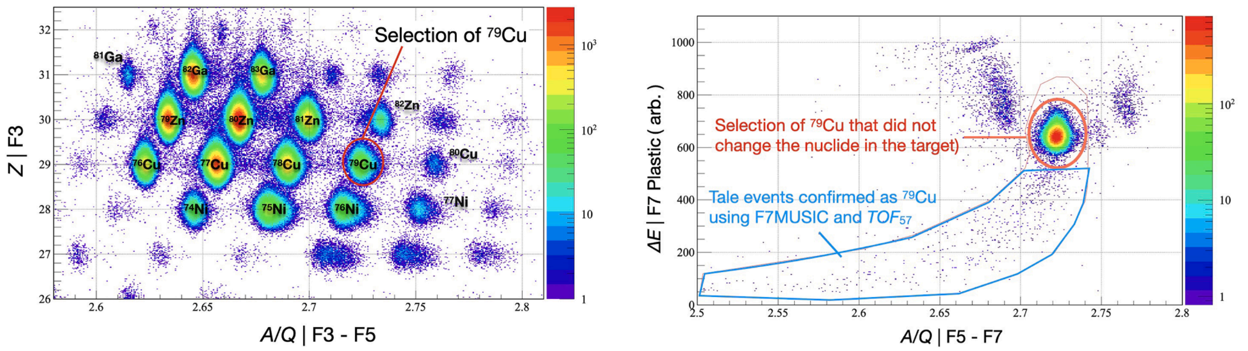


Fig. 1. Experimental Setup at BigRIPS (F3-F7).



(a) Upstream of the reaction target (F3-F5)

(b) Down stream of the reaction target (F5-F7)

Fig. 2. Particle identification for interaction cross section analysis (^{79}Cu as an example).

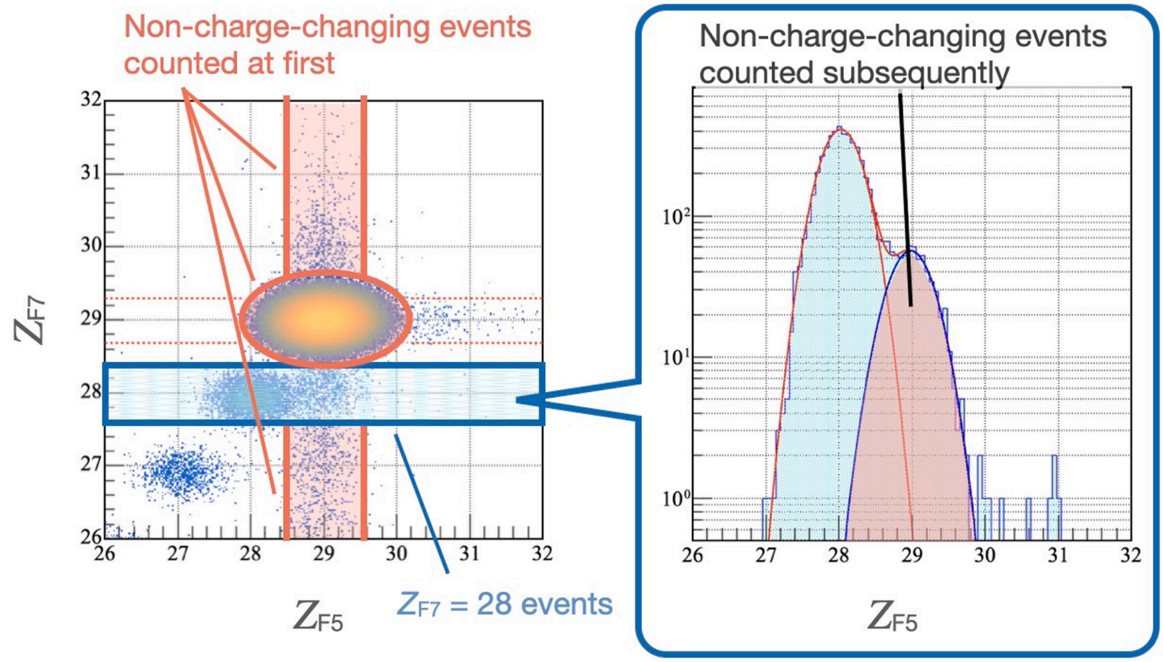


Fig. 3. Identification of non-charge-changing events.

where t is the target thickness. The transmission T_{I} is defined as the ratio of the number of outgoing particles that did not change the nuclide (N_{out}) to the number of incoming particles (N_{inc}), $T_{\mathrm{I}} = N_{\mathrm{out}}/N_{\mathrm{inc}}$. The outgoing particles that did not change the nuclide were identified similarly to the upstream analysis, based on measurements of TOF, ΔE, and $B\rho$, as shown in Fig. 2. Here, we applied emittance cuts upstream to ensure that losses due to the separator's acceptance would not be counted as reactions. This cut was chosen so that the transmission rate becomes flat as a function of the upstream emittance variables (horizontal and vertical position at F3 and F5, and momentum between F3 and F5). For the tail events highlighted in the figure, we confirmed that they are the same nuclide as the incoming particles by using F7MUSIC and downstream TOF information.

Similarly, the charge-changing cross sections (σ_{cc}) were obtained from the transmission rates of non-charge-changing particles ($T_{\mathrm{CC,in}}$ and $T_{\mathrm{CC,out}}$) using:

$$\sigma_{\mathrm{cc}} = -\frac{1}{t} \ln\left(\frac{T_{\mathrm{CC,in}}}{T_{\mathrm{CC,out}}}\right). \tag{2}$$

Here, non-charge-changing particles are those that did not change their atomic number. For the identification of non-charge-changing events, we utilized data from both the F5 and F7 MUSIC detectors to compensate for the limited resolution of the F5 MUSIC detector. First, we selected non-charge-changing events ($Z = 29$) from a two-dimensional histogram plotting the atomic number Z measured at F5 (Z_{F5}) against Z measured at F7 (Z_{F7}) (Fig. 3). However this does not capture all non-charge-changing events because some particles may undergo charge-changing between F5 and F7, or may not be transported to F7 due to acceptance limitations. Therefore,

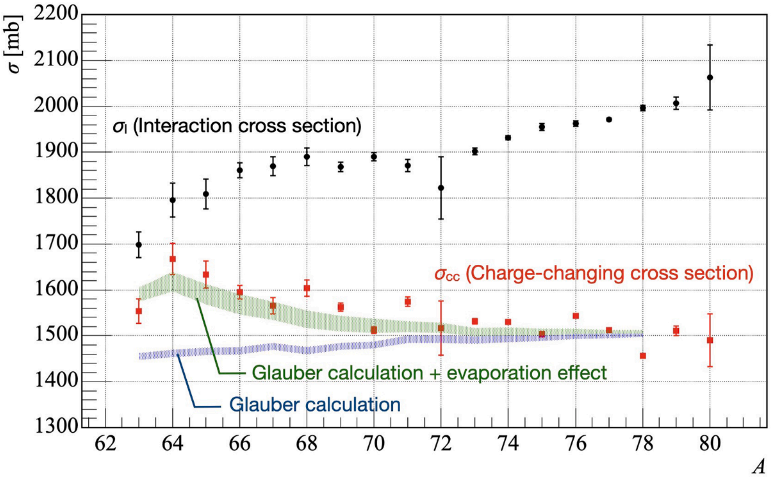


Fig. 4. Interaction- and charge-changing cross sections for Cu isotopes.

for events where $Z_{F7} = 28$, we fitted the $Z_{F5} = 29$ peak to extract non-charge-changing events identified at F5 but not at F7 (Z = 28). Similarly, for events where Z_{F7} is neither 29 nor 28 or for particles that did not reach F7, the same fitting procedure was applied. Thus, all non-charge-changing events were counted without omission.

3. Results

Fig. 4 presents the measured interaction cross sections (σ_I) and charge-changing cross sections (σ_{cc}) for copper isotopes as a function of mass number. The interaction cross sections exhibit an increasing trend with mass number, reflecting the growth of the matter radii. In contrast, the charge-changing cross sections show a decreasing trend, which is attributed to the charged-particle evaporation effect [6]. For $^{63-78}$Cu isotopes, charge radii are known from the measurements by de Groote et al. (2020) [7]. Using these measured charge radii as input, Glauber model calculations combined with evaporation effect corrections reproduce the observed charge-changing cross sections. The calculated values show good agreement with our experimental data (Fig. 4).

4. Future prospect

Further detailed analysis including Glauber calculation is necessary for deriving the matter radii of $^{63-80}$Cu and the proton distribution radii of ^{79}Cu and ^{80}Cu. Additionally, we will extract the neutron skin thickness and constrain the symmetry energy parameter L.

CRediT authorship contribution statement

G. Takayama: Conceptualization, Data curation, Formal analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing; **M. Fukuda:** Conceptualization, Investigation, Project administration, Supervision, Writing – review & editing; **M. Tanaka:** Data curation, Formal analysis, Investigation, Software; **M. Fukutome:** Data curation, Formal analysis, Investigation; **M. Takechi:** Conceptualization, Investigation, Project administration; **T. Suzuki:** Conceptualization, Investigation; **A. Homma:** Formal analysis, Investigation; **D. Nishimura:** Investigation; **T. Moriguchi:** Investigation; **D. S. Ahn:** Investigation; **A. Aimaganbetov:** Investigation; **M. Amano:** Investigation; **M. Amitani:** Investigation; **H. Arakawa:** Investigation; **H. Baba:** Data curation, Investigation; **S. Bagchi:** Investigation; **K.-H Behr:** Investigation; **N. Burtebayev:** Investigation; **K. Chikaato:** Investigation; **H. Du:** Investigation; **T. Fujii:** Investigation; **N. Fukuda:** Investigation; **C. Fukushima:** Investigation; **H. Geissel:** Investigation; **T. Hori:** Investigation; **S. Hoshino:** Investigation; **R. Igosawa:** Investigation; **A. Ikeda:** Investigation; **N. Inabe:** Investigation; **K. Inomata:** Investigation; **S. Ishitani:** Investigation; **K. Itahashi:** Investigation; **T. Izumikawa:** Investigation; **D. Kamioka:** Investigation; **N. Kanda:** Investigation; **I. Kato:** Investigation; **I. Kenzhina:** Investigation; **Z. Korkulu:** Investigation; **Y. Kuk:** Investigation; **K. Kusaka:** Investigation; **K. Matsuta:** Investigation; **M. Mihara:** Investigation; **E. Miyata:** Investigation; **D. Nagae:** Investigation; **S. Nakamura:** Investigation; **M. Nassurlla:** Investigation; **K. Nishimuro:** Investigation; **K. Nishizuka:** Investigation; **N. Noguchi:** Investigation; **M. Ohtake:** Investigation; **T. Ohtsubo:** Investigation; **S. Omika:** Investigation; **H. J. Ong:** Investigation; **K. Onishi:** Investigation; **A. Ozawa:** Investigation; **A. Prochazka:** Investigation; **S. K. Sakhiyev:** Investigation; **H. Sakurai:** Investigation; **C. Scheidenberger:** Investigation; **Y. Shimizu:** Investigation; **T. Sumikama:** Investigation; **S. Suzuki:** Investigation; **H. Suzuki:** Investigation; **R. Taguchi:** Investigation; **H. Takeda:** Investigation; **Y. Tanaka:** Investigation; **Y. Tanaka:** Investigation; **I. Tanihata:** Investigation; **Y. Togano:** Investigation; **T. Wada:** Investigation; **K. Wakayama:** Investigation; **S. Yagi:** Investigation; **T. Yamaguchi:** Investigation; **R. Yanagihara:** Investigation; **Y. Yanagisawa:** Investigation; **A. Yano:** Investigation; **K. Yasuda:** Investigation; **K. Yoshida:** Investigation; **T. K. Zholdybayev:** Investigation.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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